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Calculation of Hazard Distances for Scanning, Repetitively Pulsed Laser Systems

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Alasdair McInnes and James Richards

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ABSTRACT

This report details a methodology of evaluating the eye hazards due to scanning, repetitively pulsed laser radar systems. A computer model developed for carrying out such calculations is described in detail, and applied to an experimental laser radar system currently being developed in DSTO.

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EXECUTIVE SUMMARY

There is increasing interest within defence organisations in laser radar of one form or another, for applications such as surveillance, target recognition and tracking, remote sensing of atmospheric conditions and detection of chemical/biological species.

An important factor in the eventual mode of operation of such systems is the hazard presented to the human eye. The conduct of trials, exercises and operations is influenced by eye safety constraints. A methodology is required to evaluate these hazards so that appropriate controls may be instituted, which are neither overly restrictive nor insufficiently protective.

The nature of laser radar systems makes such calculations complex, and a methodology is not defined in the relevant Australian Standard. An approach to this problem is detailed in this report, and a computer model developed for carrying out such calculations described in detail. As an example, the model is applied to an experimental laser radar system currently being developed in DSTO.

The analysis and results of this report are expected to be of use to personnel involved in the specification, development, procurement, evaluation and operation of a wide variety of laser radar system types, as well as ADF personnel undertaking the duties of Laser Safety

Authors

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Alasdair McInnes received his B.Sc.(Hons) from Glasgow University and his M.Sc. from St. Andrews University, Scotland, in 1982 and 1983 respectively. From 1983 to 1990 he worked at Barr & Stroud Ltd, (now Pilkington Optronics), Glasgow, Scotland. During that time he worked on laser induced damage of optical materials, sensor protection, and laser development. In 1990 he joined the Australian Defence Science and Technology Organisation, where he has worked on eyesafe lasers and diode pumping of solid state lasers.

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Contents

1. Introduction

There is increasing interest within defence organisations in laser radar of one form or another, for applications such as surveillance, target recognition and tracking, remote sensing of atmospheric conditions and detection of chemical/biological species.

The majority of such systems necessitate the scanning of a repetitively pulsed laser beam over a range of angles in order to build up an image of the region of interest. It is necessary to evaluate the hazards that may be posed by the laser radiation in order to minimise the risk of injury to personnel. Laser hazards are characterised by the Nominal Ocular Hazard Distance (NOHD), which is the distance from the laser source at which the radiation intensity falls below the prescribed limit as defined in the Australian Laser Safety Standard [1]. This limit is termed the Maximum Permissible Exposure (MPE).

The Standard does not define a complete methodology for calculation of the NOHD for scanned systems, and attention in the scientific and health literature has to date been limited to supermarket scanners and ophthalmic instruments. None of this work can be extended readily to the case of interest, the outdoor use of scanning, repetitively pulsed laser systems.

This paper sets out a methodology for NOHD determination, details a computer model for performing the calculations for systems with a wide variety of parameters, and demonstrates its application to an example system, an Imaging Laser Radar (ILR) currently being developed in DSTO.

2. NOHD calculation

Calculation of the NOHD for a stationary single-pulse or cw laser beam is relatively straightforward. The MPE depends primarily on the wavelength and pulsewidth of the laser. The NOHD can then be calculated from the power/energy, the beam divergence and the initial beam width. If the laser is repetitively pulsed, the most restrictive of the limits applying to the cumulative energy density or the average power density is applied. In addition, the MPE is a function of the overall exposure time. For a scanned system, cumulative energy, average power density and overall exposure time are all functions of the scan parameters: array size and shape, angular resolution, and the "delay" - the time it takes the scan mirror to decelerate at the end of one line, change direction and reach scanning speed for the next line. The size of the aperture collecting the radiation also has significant influence.

Since the scan pattern and resolution affect the total scan time, this affects not only the exposure, but the MPE with which it must be compared. Additionally, different MPEs are quoted for eye and skin exposure.

A model has been developed that calculates the irradiance as a function of distance for given scan parameters. It then compares that with the relevant MPE values and determines the NOHD.

3. Model

3.1 Exposure scenario

The exposure received depends on the scan pattern, the delay, the beam divergence, the aperture size and the range. Only a bi-directional raster scan pattern is treated in this model.

Figure 1 shows the exposure scenario envisaged. At close range, most or all of the pulses can enter the viewing aperture as they are separated by a small angular amount, while at longer ranges only a few pulses may enter. The important factors in hazard calculations are the total energy, the number of pulses received and the total exposure time. The model calculates these factors as a function of distance.

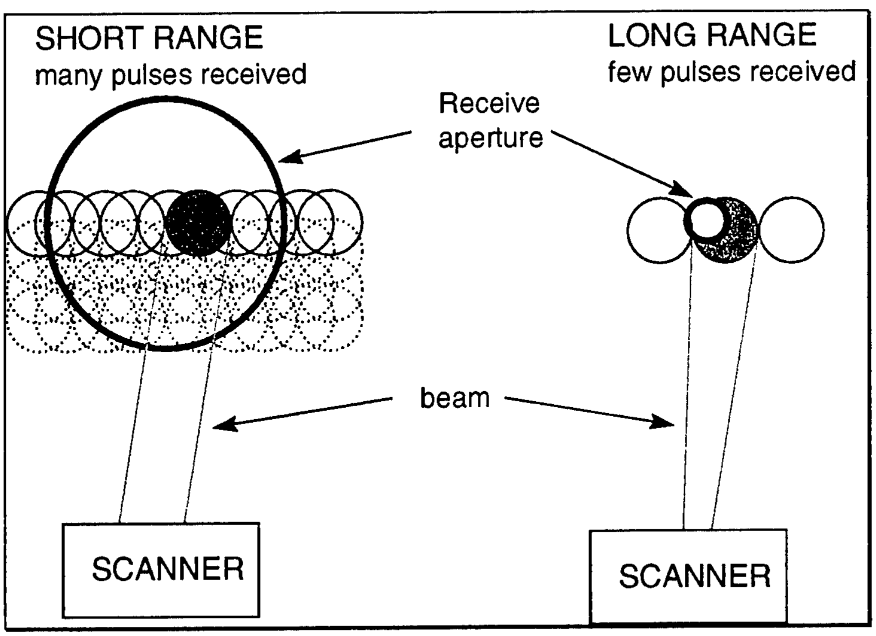


Figure 1. Exposure scenario.

The temporal behaviour of the radiation received by the viewing aperture is shown in Figure 2. Bursts of pulses are received whose length and total duration depend mostly on the relative size of the beam and aperture.

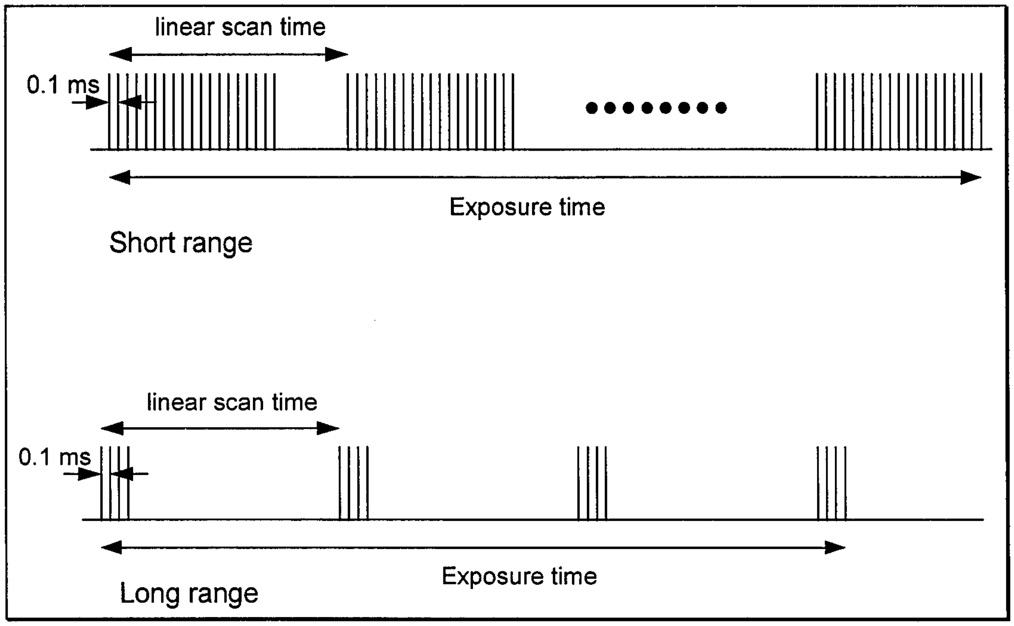


Figure 2. Temporal structure of received radiation.

We say that a pulse is received (a hit) when the centre of the smaller of the beam and the aperture falls within the larger. The beam width is taken to be the $1/e^2$ diameter. This takes account of the differences between the case when the receiver is close to the source and receives many pulses, and the case when the receiver is remote. A hit delivers all the energy of the pulse to the receiver, ie. no aperturing is taken into account.

The definition of the delay at the end of a line is shown in Figure 3. Pulses falling between scan lines are counted as if they all landed at the end of the previous line. To allow for the "worst case", each burst of hits irradiating a receiver is assumed to contain pulses emitted during the delay, ie the receiver aperture is assumed to intersect one edge of the scan pattern.

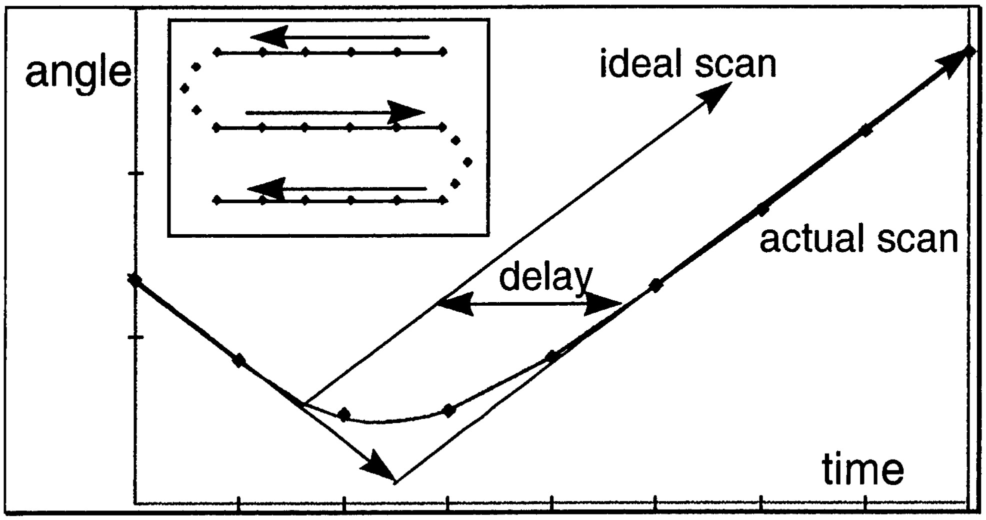


Figure 3. Behaviour of beam direction at the end of a scan line. The inset shows the effect on the scan pattern.

3.2 Assumptions

The following assumptions are made in the model:

- Atmospheric attenuation is negligible;
- Transmittance of optical aids is 100%;
- The beam is stationary during the delay at the end of each scan;
- Continuous repetitive scanning is not possible - the hazards for a single scan are evaluated
- Only one wavelength is emitted.

3.3 Exposure evaluation

A flowchart showing the main steps in calculating the hazard distances for given scan, receiver, laser and beam paramters is shown in Annex A. A printout of the MathCAD (Version 6+) worksheet used to carry out the modelling is attached at Annex C, and the Excel file used for input and output of the data is shown in Annex B.

The input scan parameters are the scan size in horizontal and vertical angles (hscan and vscan), the angular separation of adjacent points (hϕ and vϕ), and the delay at the end of a scan line (delay). The laser parameters are the power (P), the FWHM pulse duration (τ), the initial $1/e^2$ beam radius (w_0), the initial wavefront radius of curvature (R_0), the pulse repetition frequency (prf), the M^2 factor (Msq), and the wavelength (λ).

The MPEs are defined in terms of energy density (ED) or power density (PD), depending on the exposure time (exptime). In order to calculate the correct MPE, it is necessary to evaluate the number of hits.

3.3.1 Beam propagation

To calculate the number of hits and the irradiance at a given range, it is necessary to find the beam size as a function of distance. This is calculated using the Gaussian beam propagation formalism. This technique was adopted because the beam may be converging when it is emitted from the transmitter, so a simple divergence figure will not describe its behaviour at short ranges, where the hazard is greatest, and also because if the profile is non-Gaussian or unknown, it is difficult to define a specific beam diameter.

The propagation of Gaussian beams is defined by the wavelength, beam width, wavefront radius of curvature and the M^2 factor, which is a measure of beam quality in terms of how far the beam is from being diffraction-limited[2].

The beam size ($1/e^2$ radius) as a function of distance is given by

$$w(z) := \left[\frac{-\pi}{\lambda \cdot Msq} \cdot \mathrm{Im}\left[\frac{1}{\left[\frac{1}{R_0} - \frac{i \cdot \lambda \cdot Msq}{\pi \cdot (w_0)^2} \right]^{-1} + z} \right] \right]^{-0.5}$$

where R_0 is the wavefront radius of curvature, w_0 is the beam size ($1/e^2$ radius), both measured at the output of the transmitter.

The energy density of a single pulse as a function of distance propagated is then given by

$$ED(z) = E \;/\; \pi . r_b^2(z)$$

where $r_b(z)$ is the $1/e$ radius of the beam, equivalent to $w(z)/\sqrt{2}$.

This is compared with the most restrictive MPE as a function of distance, to find the NOHD.

3.3.2 Finding the MPE

Tables of values for MPEs are given in the Laser Safety Standard [1]. The main factors are the wavelength and exposure time. For a pulsed system, the exposure time may be either the laser pulse width or the total time between first and last exposure, depending on the circumstances. The process for evaluating the correct MPE with which to compare the energy density at a specific range is as follows:

Determine the wavelength
Determine the pulse width
Determine the exposure time
Determine the number of pulses (hits)
Calculate the MPE under the three conditions described in the Standard (see below) for multiple pulse exposure
Convert all into units of energy density
Select the lowest MPE
Modify the MPE to account for the presence of optical aids
Modify the MPE to account for the use of limiting apertures [1].

The three conditions are that;

a) the exposure for a single pulse within a pulse train shall not exceed the MPE for a single pulse. Here the MPE selected from the table is that for an exposure time equal to the pulse duration.
b) the total exposure for a pulse train of duration T shall not exceed the MPE for a single pulse of duration T. Here the MPE selected is that for an exposure equal to the time between first and last received pulse. It is then divided by the number of hits for comparison with the single pulse energy density.
c) The exposure for a single pulse within a pulse train shall not exceed the MPE for a single pulse divided by the number of pulses received to the power _. Here the MPE for case a) above is reduced by a factor $NP^{1/4}$, where NP is the number of hits.

There is a caveat concerned with the case where the MPE in peak power terms falls below the cw average power MPE, but since this is extremely unlikely to apply to laser radar - type systems it is not considered further.

It is clear that the number of hits and the total exposure time must be evaluated as function of distance in order to calculate the correct MPE for comparison with energy density.

3.3.2.1 *Wavelength range*

The MPE table in the model allows selection of any wavelength between 1.4 μm and 1 mm. Calculation of MPEs for wavelengths less than 1.4 μm for scanning systems is considerably complicated by the need to quantify the "angular subtense" of the source, and is outside the scope of the current model, although it could be added at a later date.

3.3.2.2 *Number of hits*

If the entire scan is within the receiver aperture, then all pulses are hits. In this case the number of hits (NP) is given by

$$NP = nv.nh + (nv-1).extra$$

where nv and nh are the number of points along the vertical and horizontal edges of the scan, and extra is the number of pulses fired during the time taken to change direction at the end of a line (assumed to affect only the horizontal direction). The value of extra is given by

$$\text{extra} = \text{delay.prf}$$

If the scan is larger than the receiver aperture, the situation is more complex. It is necessary to consider the worst case, ie. the maximum possible number of hits for a given range, aperture and scan pattern. Because there are extra pulses at the side edges of the scan, the receiver is assumed to be at one edge. The question then arises as to what relative position of aperture and scan edge gives rise to the maximum number of pulses being received. This depends on the delay at the scan edge and the density of points in the rest of the scan. If the delay was equal to zero, the maximum number of hits would occur when the array of points corresponding to the centres of successive pulses covers the full aperture. If however the delay was large and the density was low, then the maximum number would occur when the edge of the array fell somewhere between the centre and the edge of the aperture. See Figure 4.

Two different approaches are given in the model, which can be selected setting the variable "discrete" equal to 1 or 0 in the MathCAD worksheet. They are referred to as the "discrete" method and the "integral" method.

The discrete method is more exact, but more computationally intense. At each distance from the source, an array of points corresponding to the beam centres of successive pulses is created. To reduce processing time the size of the array is limited to slightly greater than the size of the aperture. A circle representing the aperture is generated and centred on the centre of the array in the vertical direction. This circle is then moved in increments horizontally across the array and the number of points inside the circle is evaluated each time. If the beam is larger than the aperture, the beam size is used to generate the circle rather than the aperture. This is equivalent to scanning the aperture over the beam rather than the other way round, and is necessary to meet the definition of a hit as given above.

A point at one end of every second row represents "extra" hits received during the turnaround delay. If the scan pattern is small enough, points at each end of the array contribute extra hits. The number of hits for this combination of scan parameters, range and aperture size is then given by the greatest number of hits found in all the iterations. Figure 4 shows this graphically.

Counting the hits in this way is considerably more accurate than approximating the beam and the aperture as square-sided and attempting to compensate for the difference by using the ratio of the area of a square and a circular receiver. It also proved more accurate than the integral method, which is described below.

In the integral method, the aperture is again assumed to intersect the edge of the scan pattern. Two distinct areas within the aperture are defined [Figure 4], Area A1 which contains the extra points due to the delay, has width equal to the horizontal spacing of the points and height equal to the vertical extent of the aperture at the position of the scan edge. The number of points in this area can be approximated to be:

$$NP_{A1}(z) = 2 \cdot \left[\frac{\sqrt{r(z)^2 - (\mathrm{offset})^2}}{dv(z)} \cdot \left(1 + \frac{\mathrm{extra}}{2}\right) \right]$$

Similarly, the number of points in area A2 can be approximated from the area and the density of points:

$$NP_{A2}(z) = \frac{2 \cdot \int_{\mathrm{offset} + \frac{dh(z)}{2}}^{r(z)} \sqrt{r(z)^2 - x^2}\, dx}{dh(z) \cdot dv(z)}$$

where the quantity "offset" is the distance between the aperture centre and the edge of the array.

To calculate NP, these two expressions are evaluated and summed for a number of values of offset, and the maximum found. This method is significantly faster than the discrete method, but suffers a certain amount of inaccuracy. This is shown in Figure 5, which compares NP calculated using each method for a range of offset values. Since the maximum of each of these plots would be returned as NP, the difference between the two methods for this set of parameters is small. However this may not hold in all cases. The value of the integral method is that it provides reasonably accurate results in a short time. The discrete method should be used for assessing the absolute value of the NOHD.

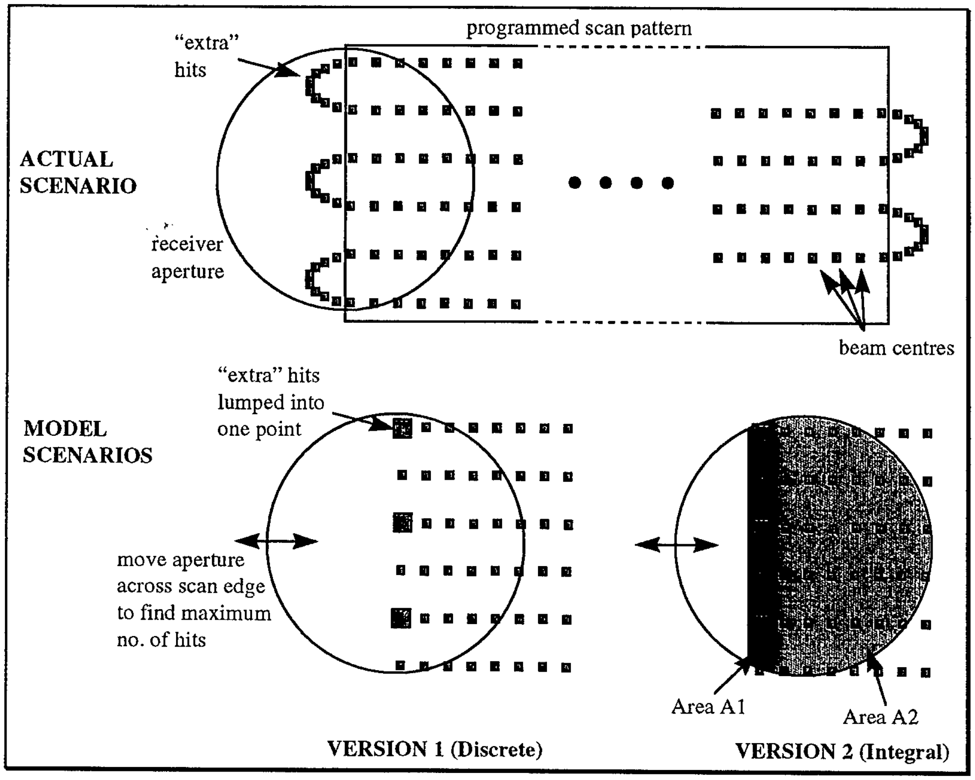


Figure 4. The two approaches to evaluating the maximum number of hits for a given scan and receiver combination. Version 1 corresponds to the "discrete" model and version 2 the "integral" model.

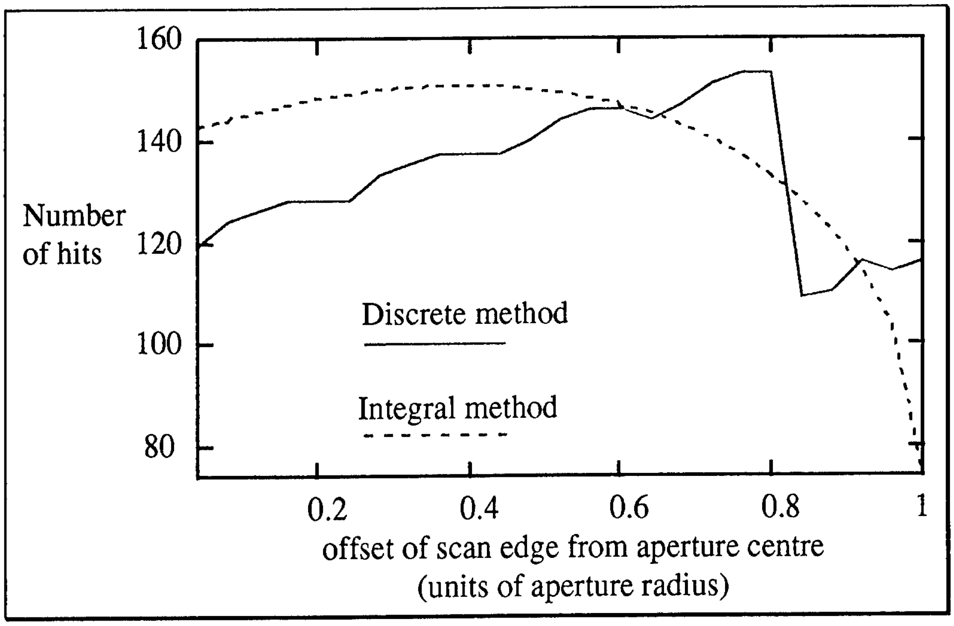


Figure 5. Comparison of discrete and integral method of counting hits. Parameters used: hscan, vscan = 2 mrad, hϕ, vϕ = 0.1 mrad, delay = 2 ms, aperture radius = 25 mm, range = 51 m. The discontinuity in the "discrete" curve is due to two edge points each contributing 21 hits moving out of the aperture.

3.3.2.3 *Exposure time*

The exposure time is the product of the number of horizontal lines falling within the aperture and the linear scan time, subject to the limit of the total scan time. This simple definition tends to overestimate the exposure time by up to one horizontal scan time, but this is considered negligible, and preferable to underestimating when the number of lines containing a hit is small.

3.3.2.4 *Units*

For all wavelengths greater than 300 nanometres, the tabulated MPE depends on the exposure time. Below a threshold exposure time, which for most wavelengths is 10 seconds, the MPE is expressed in terms of energy density, so the MPE, modified according to case a), b) or c) as in Section 3.2.2 must be compared with the energy density of a single pulse. Above the threshold, the MPE is in power density, and is converted to energy density by multiplying by the exposure time.

3.3.2.5 *Optical aids*

In addition, where there is the possibility of optical aids such as binoculars being used, the MPE is modified (decreased) by an optical gain factor. This factor is either the ratio of the area of the objective lens to that of the eye or the square of the magnification, the latter if the beam size is smaller than the objective.

3.3.2.6 *Limiting aperture*

The use of limiting apertures is defined in the Standard [1]. The idea is that if a beam is smaller than a receiver, it is the total energy/power received that is important rather than the energy/power density at the receiver input.

In the model this means that when the beam is smaller than a certain size, known as the limiting aperture, the energy is assumed to be averaged over the entire limiting aperture. Values for the limiting aperture, which depend on wavelength and exposure time, are defined in the Standard [1].

In practice this is taken into account by modifying the MPE, by increasing it by the square of the ratio of the beam and limiting aperture radii.

3.3.2.7 *Skin exposure*

Separate MPEs are defined for skin exposure as well as eye exposure. Additionally, for some wavelengths and exposure times the MPE is reduced if the beam area exceeds 0.1 m^2. Only lasers having an output power greater than 10 W are capable of exceeding this limit, so if the laser is of lesser output this restriction need not be considered.

NOHDs must be calculated for both ocular and skin exposure.

3.3.3 Running the model

The model is run by calling the MathCAD worksheet from an Excel Macro, which allows a table of results to be generated. It can also be run be using the MathCAD worksheet alone, and setting the input parameters within the worksheet. This generates one value of each output (eg NOHDeye) each time the worksheet is executed.

A typical data entry and output table and a listing of the Excel Macro is given in Annex B, and listings of the two MathCAD worksheets are given in Annex C.

3.3.3.1 *Using the Excel Macro*

In order to use the Excel Macro, the following procedure should be followed:

- Open Excel
- Open file "NOHD of scanned systems.xls"

- Enter a table of input data in columns B to O, starting in row 16
- Check that the path in cell W5 is correct for the MathCAD worksheet
- Open MathCAD (Version 6+)
- Open file "NOHD of scanned systems.mcd"
- In Excel, position the cursor in cell W4
- Right-click the mouse
- Select "Run" from the menu
- Select "Run" from the "Macro" window that opens (note: there are other ways of running the macro)

The macro will now run, transferring input data from the table to the MathCAD worksheet, and inserting the results in the output part of the table, row by row until it has completed the last row, then stops. The results can then be used to generate plots or be manipulated in other ways - but they must be copied to another Excel worksheet first. Excel does not allow calculations or plots in a "macro" worksheet.

3.3.3.2 *Divergence as an input*

It may be desirable to input a range of divergences instead of a range of wavefront radii. Because the model calculates divergence from wavefront radius, this has to be done by first calculating the radii that correspond to the desired divergences, inserting them in the table. The model provides divergence as an output, not an input.

A MathCAD worksheet has been created that calculates divergence from given wavefront radius (and M-squared, w_0 and λ), and also has the capability of generating a table of wavefront radius given a range of divergences.

The procedure is as follows:

- Open MathCAD (Version 6+)
- Open file "divergence vs wavefront radius.mcd"
- Using the lower part of the sheet and the range variable "i", set up the desired range of divergences
- On executing the worksheet, the corresponding range of wavefront radii are displayed.

Care is required however, as each divergence has two solutions in wavefront radius, one positive and one negative (but of the same magnitude). These correspond to divergent and convergent output beams from the scanner. It is important to select the correct one for the application as this can affect the NOHD considerably.

If the "solve block" fails to find the radius for a given divergence, the solution can be obtained manually using the upper part of the worksheet, varying R_0 until the desired divergence is obtained

4. Example

This section contains an example calculation of the NOHDs for a scanning laser rangefinder system under development in DSTO called the Imaging Laser Radar.

4.1 Input data

The following input data is used for the calculation:

- The wavelength is 1.54 μm.
- The total average output power is 1.6 watts, made up of 0.16 mJ pulses at a prf of 10 kHz;
- The beam is round and Gaussian in profile with a $1/e^2$ radius of 11 mm and an M^2 value of 1.36;
- The scan pattern can be varied from 2 x 2 pixels to 10 x 10 degrees - it is restricted to a square pattern to simplify analysis;
- The initial radius of curvature of the wavefront can be varied from 20 m diverging, through $\pm\infty$ (collimated) to 10 m converging, corresponding to a range of far field divergence of 0.1 to 1 mrad;
- The delay is 2 ms;

4.2 MPE evaluation

The MPE figures with which the exposures calculated in the above section must be compared are dependent on the exposure time, which is denoted exptime(z). For the eye, the MPE is

MPE_{eye} = 10000 J.m^{-2} (exptime(z) < 10 s)
MPE_{eye} = 1000 W.m^{-2} (exptime(z) ≥10 s)

For the skin, we have

MPE_{skin} = 100 J.m^{-2} (exptime(z) < 10^{-7} s)
MPE_{skin} = 5600 . exptime(z)$^{1/4}$ J.m^{-2} (exptime(z) < 10 s)
MPE_{skin} = 1000 W.m^{-2} (exptime(z) ≥10 s, beam area < 0.1 m^2)
MPE_{skin} = 100 W.m^{-2} (exptime(z) ≥10 s, beam area ≥ 0.1 m^2)

The power of the laser is such that this last skin limit cannot be reached.

4.3 Results

The model has been used to calculate the NOHD for the skin and for optically aided viewing using 7 × 50 binoculars as a function of beam radius of curvature for a variety of scan step sizes. The results are shown in Figures 6 and 7 below.

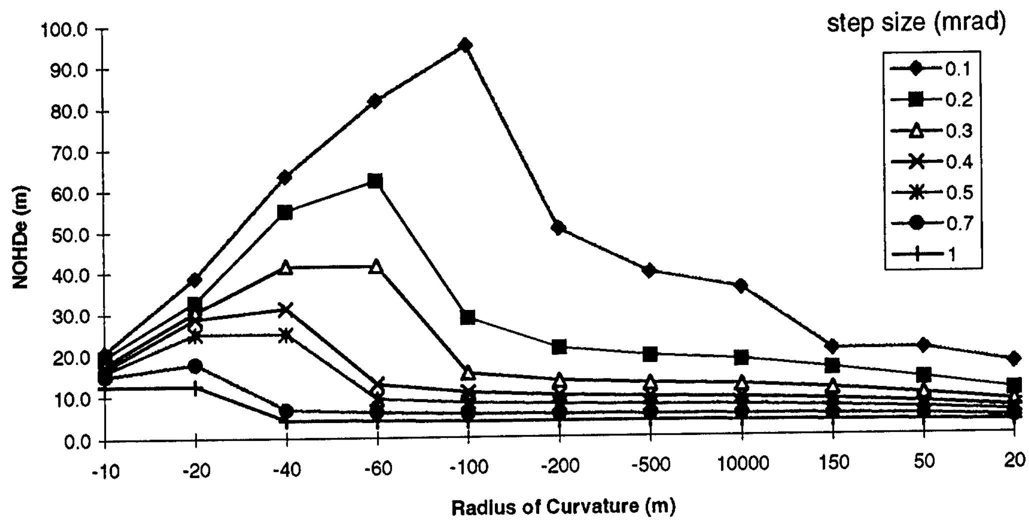


Figure 6. NOHDe for 7 × 50 binoculars as a function of beam radius of curvature, with a delay of 2 ms.

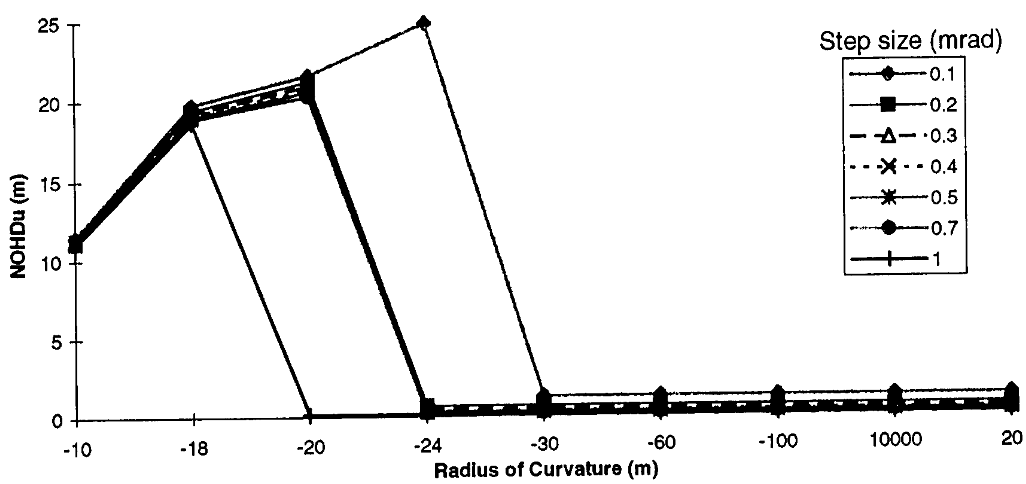


Figure 7. NOHD for skin as a function of scan angle, resolution 0.1 and 1 mr, with a delay of 2 ms.

It can be seen that the most restrictive case is with a step size of 0.1 mrad, ie the finest resolution scan. The NOHD for 7 x 50 binoculars is some 95 m for a radius of curvature of 100 m. The skin hazard is small, with the NOHD extending to no more than 25 m in the worst case when the beam is focused. Figure 8 below shows the NOHD for the naked eye, which extends to 10.6 m when the beam is focused at 10 m, but falls below 2 m for all other radii of curvature that the ILR can produce. The fact that the eye hazard is less than the skin hazard is due to the definitions of the respective MPEs in the Standard [1].

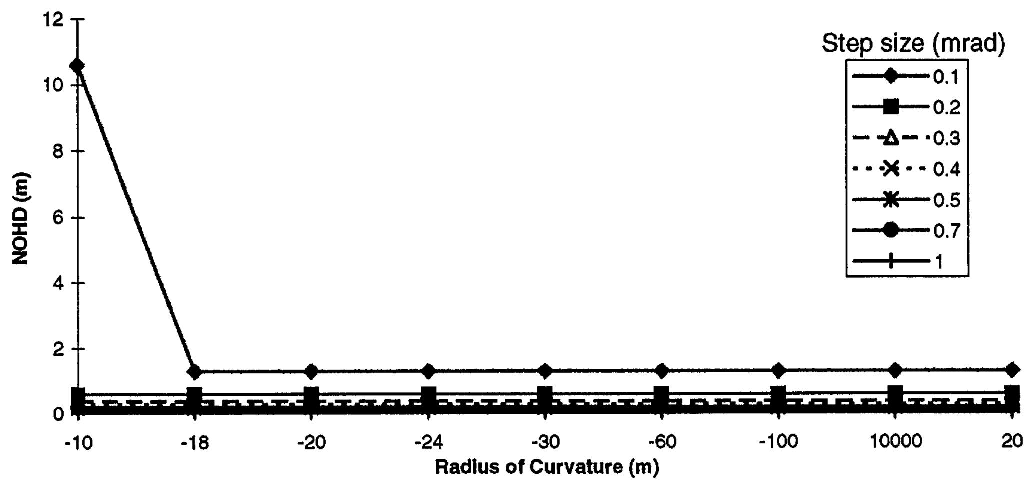


Figure 8. NOHD for the unaided eye.

If we now allow the radius of curvature to vary over the same range of magnitude, but be of either sign, we see the importance of knowing the beam parameters in the near field. Figure 9 shows NOHD as a function of divergence for beams which were initially converging and diverging on leaving the scanner.

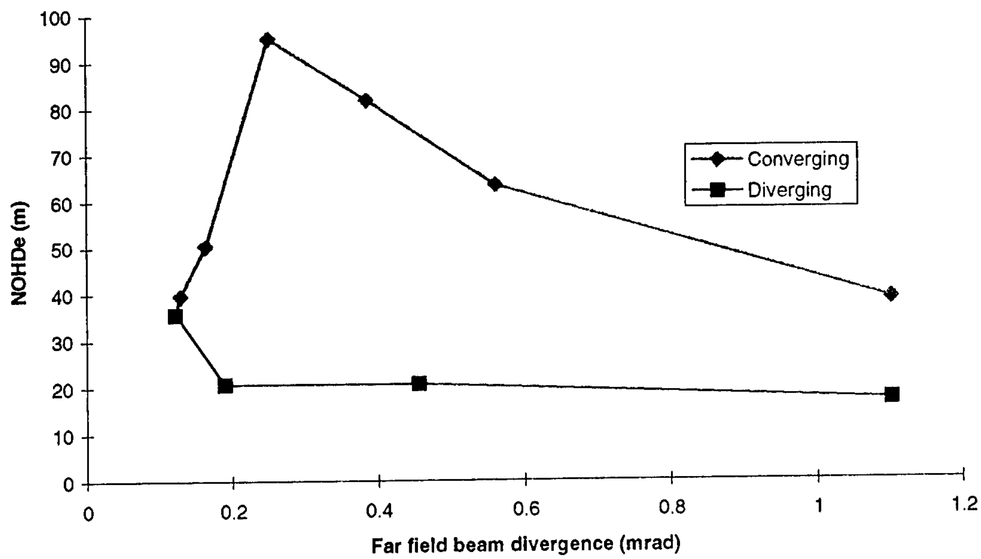


Figure 9. NOHDe for 7 × 50 binoculars as a function of far field beam divergence for beams initially converging and initially diverging.

If the divergence was determined by a far-field measurement and the setting of the beam expander was not known, a situation could arise where in the worst case the NOHD is underestimated by almost a factor of 5.

4.4 Use in dynamic safety feature

The ILR system includes a dynamic safety feature that allows it to switch to a "safe mode" of operation on detection of an object within the hazard zone for its current settings.

It does this by monitoring the range returns on a shot-to-shot basis and comparing them with a computed value for the NOHDe. Because the calculations are computationally intensive, this requires a look up table of NOHDe values as a function of step size and collimation telescope setting.

The model has been used to calculate the safe operating range for the ILR in the field, over a range of step size and telescope settings, and a look up table has been generated that gives the NOHDe for a wide but discrete range of scan/divergence conditions. The ILR's software will use interpolation to calculate the appropriate NOHDe for any combination of beam radius of curvature (ROC) or scan step size that might be used in the field. The look up table is given below:

Table 1: NOHDe in metres for ILR

ROC (m)	Step Size (mrad)						
	0.1	0.2	0.3	0.4	0.5	0.7	1
-10	20.6	19.5	17.7	16.6	15.9	14.9	12.5
-20	38.8	32.9	30.4	28.8	25.0	17.8	12.5
-40	63.5	55.1	41.6	31.2	25.0	6.8	4.3
-60	81.8	62.4	41.6	12.8	9.3	6.1	4.0
-100	95.1	28.7	15.3	10.7	8.3	5.7	3.9
-200	50.4	21.2	13.4	9.8	7.7	5.4	3.8
-500	39.6	19.2	12.6	9.4	7.5	5.3	3.7
10000	35.7	18.2	12.2	9.2	7.3	5.2	3.7
150	20.6	16	11.1	8.5	6.9	5.0	3.6
50	20.6	13.5	9.7	7.6	6.3	4.7	3.4
20	17.1	10.7	8.0	6.4	5.4	4.1	3.0

In the case where optical viewing aids can be eliminated from consideration the appropriate look up table is that for the NOHD of the skin. The look up table for this is given below.

Table 2: NOHDskin in metres for ILR

ROC (m)	Step Size (mrad)						
	0.1	0.2	0.3	0.4	0.5	0.7	1
-10	11.5	11.3	11.2	11.2	11.1	11.1	11.0
--18	19.8	19.4	19.2	19.1	19.0	18.8	18.7
-20	21.6	21.2	21.0	20.8	20.6	20.3	0.2
-24	24.9	0.7	0.5	0.4	0.3	0.2	0.2
-30	1.3	0.7	0.5	0.4	0.3	0.2	0.2
-60	1.3	0.7	0.5	0.4	0.3	0.2	0.2
-100	1.3	0.7	0.5	0.4	0.3	0.2	0.2
10000	1.3	0.7	0.5	0.4	0.3	0.2	0.2
20	1.3	0.7	0.5	0.4	0.3	0.2	0.2

5. Conclusions

A model has been developed that allows determination of the hazard distances for scanning repetitively pulsed laser systems. This is expected to be of increasing importance as systems based on such devices find more application and are fielded more widely. Systems with wavelengths between 1.4 μm and 1 mm can be evaluated.

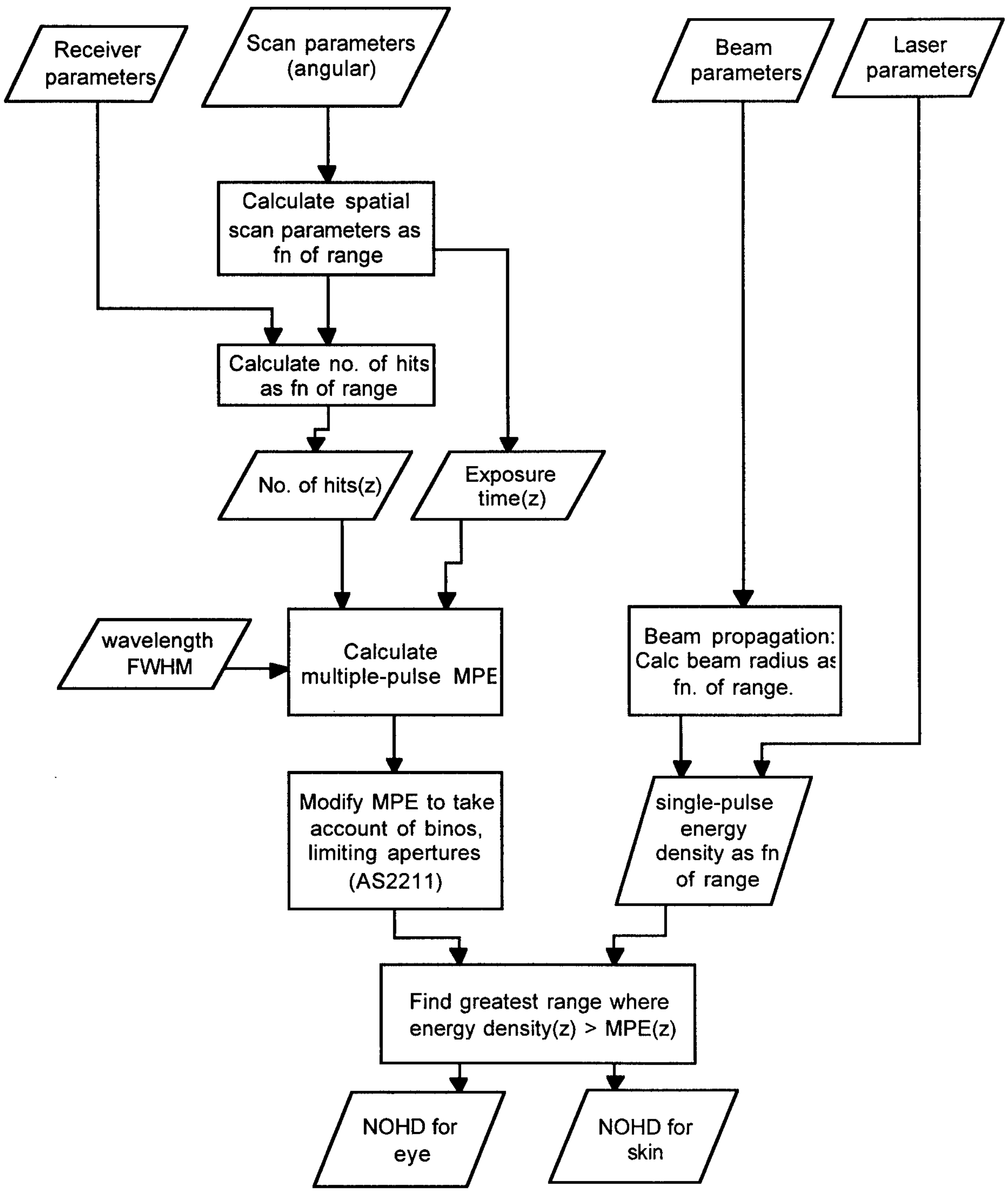
The model has been used to calculate the envelope of NOHDs that apply to the Imaging Laser Radar demonstrator, currently being developed in DSTO. Knowledge of these values will be crucial to the adoption of appropriate safety procedures during trials of the system.

6. References

1. AS/NZS 2211.1:1997 "Laser Safety", Standards Australia, Homebush, NSW 2140.

2. A E Seigman, "New developments in laser resonators", SPIE 1224, 2, (1990).

Annex A: Flowchart



Annex B: Excel File

Data input/output table

SCAN					LASER							OTHER		OUTPUT				
hscan	vscan	φh	φv	delay	power	prf	wavelength	FWHM	Msquared	w_0	R_0	BINOs	METHOD	div	Np	exptime	NOHD opt	NOHD skin
rad	rad	rad	rad	s	watt	Hz	micron	ns		m	m	1-present	1-discrete	mrad		s	m	m
							(1.4 - 1000)					0-absent	0-integral					
0.0002	0.0002	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	49	0.005	0	0
0.0004	0.0004	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	105	0.011	0	0
0.0008	0.0008	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	170	0.023	46.609	0
0.0016	0.0016	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.041	45.01	0
0.0032	0.0032	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.058	45.01	0
0.0064	0.0064	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.094	45.01	3.56
0.0128	0.0128	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.164	45.01	4.8
0.0256	0.0256	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.305	45.01	4.659
0.0512	0.0512	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	0.586	45.01	4.076
0.1024	0.1024	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	1.15	45.01	3.36
0.2048	0.2048	0.0001	0.0001	0.002	2	10000	1.54	5	1.5	0.01	13500	1	0	0.147	179	2.276	45.01	2.539

Macro

```
            DDE Macro
send        =INITIATE("MCAD","d:\alasdair\winmcad\safety\NOHD of scanned systems.mcd")
            =SELECT(INDEX(!$B$16,1,1))
L           =POKE(send,"hscan",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"vscan",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"resh",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"resv",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"del",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"Power",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"PRF",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"lambda",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"FWHM",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"Msq",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"w_out",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"R_out",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"BINO",ACTIVE.CELL())
            =SELECT("R[]C[1]")
            =POKE(send,"discrete",ACTIVE.CELL())
divergence  =REQUEST(send,"diverg")
            =SELECT("R[]C[1]")
            =FORMULA(divergence)
No_of_points =REQUEST(send,"Npts")
            =SELECT("R[]C[1]")
            =FORMULA(No_of_points)
exptime     =REQUEST(send,"TEXP")
            =SELECT("R[]C[1]")
            =FORMULA(exptime)
NOHDopt     =REQUEST(send,"NOHDopt")
            =SELECT("R[]C[1]")
            =FORMULA(NOHDopt)
NOHDskin    =REQUEST(send,"NOHDskin")
            =SELECT("R[]C[1]")
            =FORMULA(NOHDskin)
            =SELECT("R[1]C[-18]")
            =IF(CELL("type")="b",GOTO(Q))
            =GOTO(L)
            =TERMINATE(send)
Q           =RETURN()
```

Annex C: MathCAD worksheets

Set input parameters for single use or receive input values from Excel Macro

The transfer from Excel doesn't allow greek characters or units, so some have to be redefined.

Scan parameters

$hscan := 0.2048$		Horizontal scan angle (rad)
$vscan := 0.2048$		Vertical scan angle (rad)
$resh := 0.0002$	$\phi h := resh$	Horizontal pixel angular separation (rad)
$resv := 0.0002$	$\phi v := resv$	Vertical pixel angular separation (rad)
$del := 0.002$	$delay := del \cdot sec$	Delay at end of scan line due to mirror turnaround (sec)

Laser parameters

$Power := 2$	$P := Power \cdot watt$	Laser average power (Power in Watts)
$PRF := 10000$	$prf := PRF \cdot sec^{-1}$	Pulse repetition frequency (PRF in Hz)
$lambda := 1.54$	$\lambda := lambda \cdot 10^{-6}$	Wavelength (lambda in microns, 1.4 - 1000)
$FWHM := 5$	$\tau := FWHM \cdot 10^{-9} \cdot sec$	Pulse width (FWHM in ns)

Beam parameters

$Msq := 1.5$		M-squared value
$w\_out := 0.01$	$w_0 := w\_out$	$1/e^2$ radius at output of scanner (m)
$R\_out := 13500$	$R_0 := R\_out$	Wavefront radius at output of scanner (m)

Other model parameters

$BINO := 1$	Are (7x50) binoculars present? 1=yes, 0=no
$discrete := 0$	Use "discrete" or "integral" method of counting hits? 0=integral, 1=discrete

NOTE re UNITS: All dims are in metres, but not labelled explicitly, as some subroutines had problems with dimensions

Define receiver aperture parameters

$d_{eye} := 0.007 \qquad r_{eye} := \frac{d_{eye}}{2}$ — size of eye (m)

$d_{bino} := 0.05 \qquad r_{bino} := \frac{d_{bino}}{2} \qquad M := 7$ — size and magnification of binoculars

$r_a := \mathrm{if}(BINO = 1, r_{bino}, r_{eye}) \qquad A_a := \pi \cdot r_a^{\,2}$ — size and area of receiver

---

Beam propagation

$$w_b(z) := \left[-\frac{\pi}{\lambda \cdot Msq} \cdot \mathrm{Im}\left[\frac{1}{\left(\frac{1}{R_0} - \frac{i \cdot \lambda \cdot Msq}{\pi \cdot w_0^{\,2}} \right)^{-1} + z} \right] \right]^{-0.5}$$

1/e² radius of beam as a function of range

$r_b(z) := \frac{w_b(z)}{\sqrt{2}} \qquad A_b(z) := \pi \cdot r_b(z)^2$ — 1/e radius, area of beam as a function of range

$diverg := (w_b(10000) - w_b(9000)) \cdot 2$ — Calculate and display 1/e² full angle divergence

$diverg = 0.147$ — Print explicitly for output to Excel

$r(z) := \mathrm{if}(r_b(z) < r_a, r_a, r_b(z))$ — larger of beam and aperture as a function of range

NOTE: If specific divergences are required, ie. divergence is an input rather than an output, use worksheet "divergence vs wavefront radius.MCD" to calculate relevant R_0 values for the desired range of M-squared and divergence, and enter these in the Excel input spreadsheet.

Further scan pattern parameters

$$nv := \mathrm{ceil}\left(\frac{vscan}{\phi v}\right) + 1 \qquad v(z) := vscan \cdot z \qquad dv(z) := \phi v \cdot z$$

$$nh := \mathrm{ceil}\left(\frac{hscan}{\phi h}\right) + 1 \qquad h(z) := hscan \cdot z \qquad dh(z) := \phi h \cdot z$$

Calculate number of pulses in both dimensions. Define size of scan and spacing of points in distance terms as a function of range

$$extra := delay \cdot prf$$

No. of extra points at the end of a line

$$npts := nv \cdot nh + (nv - 1) \cdot extra \qquad scantime := \frac{npts}{prf}$$

Total no. of pulses in scan, total scan time

$$Nhoriz(z) := \mathrm{if}\left[\frac{v(z)}{2} < r(z), nv, \left(\mathrm{ceil}\left(\frac{r(z) \cdot 2}{dv(z)}\right)\right)\right]$$

No of horizontal scans containing a hit

$$Thoriz := \frac{nh}{prf} + delay$$

Horizontal scan time

EVALUATE NUMBER OF HITS

DISCRETE METHOD

First limit size of scan for consideration to minimum capable of delivering max. no of hits

$$X1(z) := \mathrm{if}\left(\frac{h(z)}{2} > r_a, -r_a, -\frac{h(z)}{2}\right) \qquad X2(z) := \mathrm{if}\left(\frac{h(z)}{2} > r_a, r_a + dh(z), \frac{h(z)}{2}\right)$$

$$Y1(z) := \mathrm{if}\left(\frac{v(z)}{2} > r_a, -dv(z) \cdot \mathrm{ceil}\left(\frac{r_a}{dv(z)}\right), -\frac{v(z)}{2}\right) \qquad Y2(z) := \mathrm{if}\left(\frac{v(z)}{2} > r_a, dv(z) \cdot \mathrm{ceil}\left(\frac{r_a}{dv(z)}\right), \frac{v(z)}{2}\right)$$

Define positions of corners of reduced array for discrete calculation method

Subroutine for counting hits within circular aperture/beam due to rectangular array of pulses

```
hitcounter(startx, starty, dx, dy, endx, endy, h, v, r, X11) := | count ← 0
                                                               | count ← | nv·nh + (nv − 1)·extra  if [ (v/2)^2 + (h/2)^2 < r^2 ]
                                                               |         | otherwise
                                                               |         |   for x ∈ startx, startx + dx .. endx
                                                               |         |     | county ← 0
                                                               |         |     | for y ∈ starty, starty + dy .. endy
                                                               |         |     |   | count ← count + 1  if (x + X11)^2 + y^2 ≤ r^2
                                                               |         |     |   | logic ← (x = startx)·(mod(county, 2) > 0) + (x = startx + h)·(mod(county, 2) = 0)
                                                               |         |     |   | count ← count + extra  if [ (x + X11)^2 + y^2 ≤ r^2 ]·logic
                                                               |         |     |   | county ← county + 1
                                                               |         |   count
                                                               | count
```

Subroutine for executing discrete hit count as a function of aperture/scan edge relative position, and finding maximum.

NN := 15 number of iterations across aperture/beam radius

```
N_disc(NN, startx, starty, dx, dy, endx, endy, h, v, r) := | for k ∈ 0 .. NN
                                                           |   | XC_k ← k·r / NN
                                                           |   | A_k ← hitcounter(startx, starty, dx, dy, endx, endy, h, v, r, XC_k)
                                                           | B ← max(A)
```

INTEGRAL METHOD

Subroutine for evaluating number of hits by integrating hit densities in different regions of the aperture.
This is also incremented across the edge of the scan pattern.

$$N_{int}(NN, dx, dy, h, v, r) := \left| \begin{array}{l} \text{for } k \in 0..NN \\ \quad \left| \begin{array}{l} XC_k \leftarrow \dfrac{k \cdot r}{NN} \\ A_k \leftarrow 2 \cdot \left[\dfrac{\displaystyle\int_{-XC_k + \frac{dx}{2}}^{r} \sqrt{r^2 - x^2}\, dx}{dy \cdot dx} + \dfrac{\sqrt{r^2 - (XC_k)^2}}{dy} \cdot \left(1 + \dfrac{extra}{2}\right) \right] \end{array} \right. \\ B \leftarrow \text{if}\left[r^2 > \left[\left(\dfrac{v}{2}\right)^2 + \left(\dfrac{h}{2}\right)^2 \right], \text{ceil}(nv \cdot nh + ((nv - 1) \cdot extra)), \max(A) \right] \end{array} \right.$$

Define "Number of hits" function, depending which method was chosen

$$N_p(NN, startx, starty, dx, dy, endx, endy, h, v, r) := \text{if}\left(discrete = 1, N_{disc}(NN, startx, starty, dx, dy, endx, endy, h, v, r), N_{int}(NN, dx, dy, h, v, r)\right)$$

Define base MPE values to be used from table in AS2211. Eye MPEs are dependent on wavelength and exposure time, skin MPEs depend on exposure time and exposure area (over wavelength range 1.4 microns to 1mm).

$$
MPE_{eyetable}(T,\lambda) := \left|\begin{array}{l}
MPE1 \leftarrow 100 \\
MPE2 \leftarrow 1000 \\
MPE3 \leftarrow 10000 \\
MPE4 \leftarrow 5600 \cdot T^{0.25} \\
MPE5 \leftarrow 1000 \cdot T \\
\text{if}\left[T<10,\left(\text{if}\left(T<10^{-3},MPE2,MPE4\right)\right),MPE5\right] \ \text{ if } \ (\lambda \ge 1.4)\cdot(\lambda<1.5)+(\lambda \ge 1.8)\cdot(\lambda<2.6) \\
\text{if}(T<10,MPE3,MPE5) \ \text{ if } \ (\lambda \ge 1.5)\cdot(\lambda<1.8) \\
\text{if}\left[T<10,\left(\text{if}\left(T<10^{-7},MPE1,MPE4\right)\right),MPE5\right] \ \text{ if } \ (\lambda \ge 2.6)\cdot\left(\lambda \le 10^{6}\right) \\
-1 \ \text{ otherwise}
\end{array}\right.
$$

$$
MPE_{skintable}(T,A) := \left|\begin{array}{l}
MPE1 \leftarrow 100 \\
MPE4 \leftarrow 5600 \cdot T^{0.25} \\
MPE5 \leftarrow \text{if}(A<0.1,1000 \cdot T,100 \cdot T) \\
MPE1 \ \text{ if } \ T<10^{-7} \\
MPE4 \ \text{ if } \ \left(T \ge 10^{-7}\right)\cdot(T<10) \\
MPE5 \ \text{ otherwise}
\end{array}\right.
$$

Calculate NOHDs by comparing energy density and MPE as a function of distance from laser

$zinc := 10 \quad zstart := 1 \quad zend := 151$

Establish a range of distances at which to compare energy density and MPE
For speed use large zinc, for accuracy use small zinc.

$i := zstart, zstart + zinc .. zend$

$NP_i := N_p(NN, X1(i), Y1(i), dh(i), dv(i), X2(i), Y2(i), h(i), v(i), r(i))$

$NHORIZ_i := Nhoriz(i) \qquad A_{b_i} := A_b(i) \qquad r_{b_i} := r_b(i)$

Vectorize relevant functions to reduce computation

$exptime_i := if\left[npts > Re\left(NP_i\right), \left(NHORIZ_i\right) \cdot Thoriz, scantime\right]$

$$spenergydensity_i := \frac{P}{A_{b_i} \cdot prf}$$

$r_{lim_i} := if\left(exptime_i > 3 \cdot sec, 0.00175, 0.0005\right)$

Evaluate the three "multiple pulse" MPEs (AS2211)

$$MPE\_A_{eye_i} := MPE_{eyetable}\left(\frac{\tau}{sec}, \lambda \cdot 10^6\right) \cdot joule \qquad MPE\_A_{skin_i} := MPE_{skintable}\left(\frac{\tau}{sec}, A_{b_i}\right) \cdot joule$$

Single pulse condition

$$MPE\_B_{eye_i} := \frac{MPE_{eyetable}\left(\frac{exptime_i}{sec}, \lambda \cdot 10^6\right)}{NP_i} \cdot joule \qquad MPE\_B_{skin_i} := \frac{MPE_{skintable}\left(\frac{exptime_i}{sec}, A_{b_i}\right)}{NP_i} \cdot joule$$

Total exposure condition

$$MPE\_C_{eye_i} := \frac{MPE\_A_{eye_i}}{\left(NP_i\right)^{0.25}} \qquad MPE\_C_{skin_i} := \frac{MPE\_A_{skin_i}}{\left(NP_i\right)^{0.25}}$$

$N^{1/4}$ condition

Find the most restrictive case at each range

$$MPE_{eye_i} := \min\left(\left(MPE\_A_{eye_i}\quad MPE\_B_{eye_i}\quad MPE\_C_{eye_i}\right)\right) \qquad MPE_{skin_i} := \min\left(\left(MPE\_A_{skin_i}\quad MPE\_B_{skin_i}\quad MPE\_C_{skin_i}\right)\right)$$

$$multpulse_i := if\left[MPE\_A_{eye_i} < \min\left(\left(MPE\_B_{eye_i}\quad MPE\_C_{eye_i}\right)\right), 1, if\left[MPE\_B_{eye_i} < \min\left(\left(MPE\_A_{eye_i}\quad MPE\_C_{eye_i}\right)\right), 2, 3\right]\right]$$

Modify MPE skin if beam smaller than limiting aperture

$$MPE_{skin_i} := if\left[r_{b_i} < r_{lim_i}, MPE_{skin_i}\cdot\left(\frac{r_{lim_i}}{r_{b_i}}\right)^2, MPE_{skin_i}\right]$$

Modify MPEeye if binoculars present and if beam smaller than limiting aperture

$$MPE_{optical_i} := if\left[BINO=1, if\left[r_{b_i} < r_{lim_i}\cdot M, MPE_{eye_i}\cdot\left(\frac{r_{lim_i}}{r_{b_i}}\right)^2, \frac{MPE_{eye_i}}{M^2}\right], if\left[r_{b_i} < r_{lim_i}, MPE_{eye_i}\cdot\left(\frac{r_{lim_i}}{r_{b_i}}\right)^2, MPE_{eye_i}\right]\right]$$

$$facapcorr_i := if\left[BINO=1, if\left[r_{b_i} < r_{lim_i}\cdot M, \left(\frac{r_{lim_i}}{r_{b_i}}\right)^2, \frac{1}{M^2}\right], if\left[r_{b_i} < r_{lim_i}, \left(\frac{r_{lim_i}}{r_{b_i}}\right)^2, 1\right]\right]$$

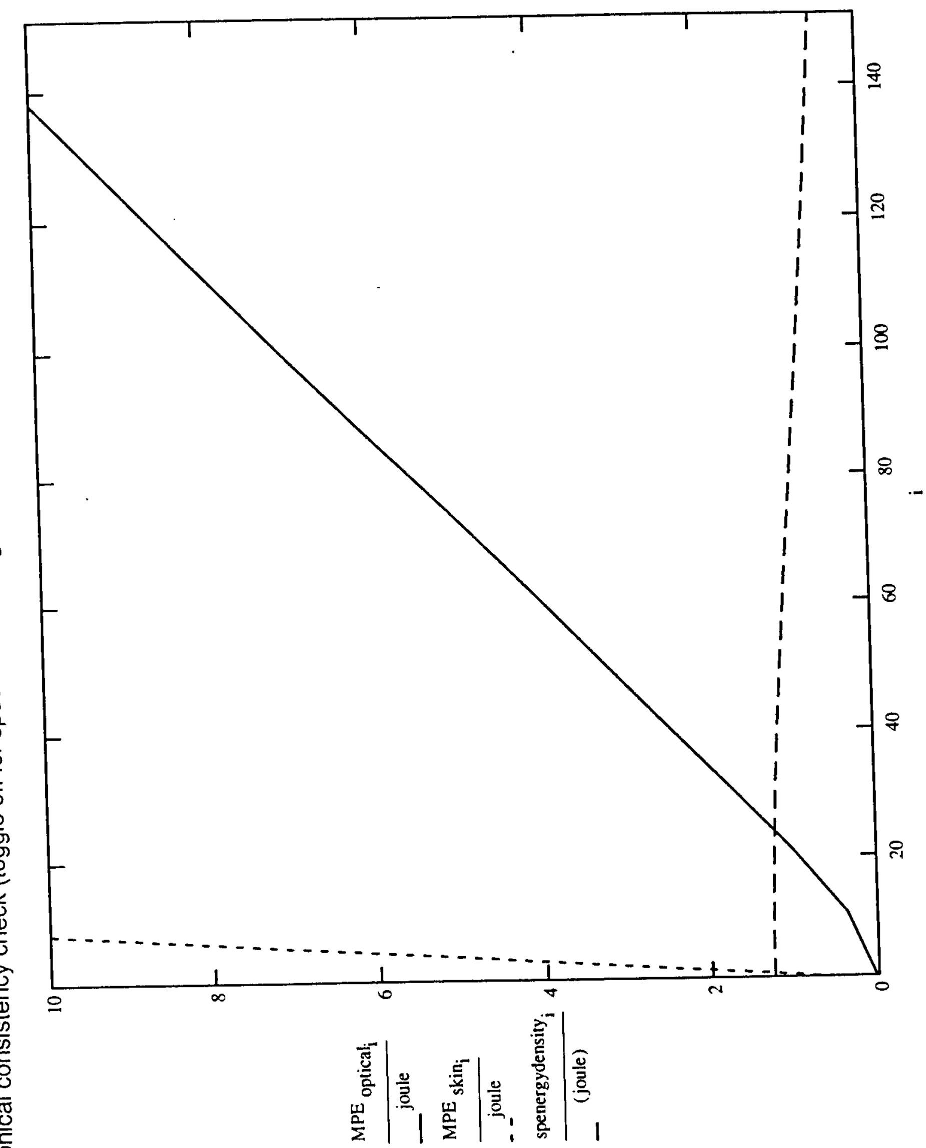
amount of correction due to bino/limiting aperture

Evaluate NOHDs with accuracy of magnitude equal to zinc

$$Nopt_i := if\left(spenergydensity_i > Re\left(MPE_{optical_i}\right), i, 0\right) \qquad roughNOHD_{optical} := \max(Nopt) \qquad roughNOHD_{optical} = 21$$

$$Nskin_i := if\left(spenergydensity_i > Re\left(MPE_{skin_i}\right), i, 0\right) \qquad roughNOHD_{skin} := \max(Nskin) \qquad roughNOHD_{skin} = 1$$

Graphical consistency check (toggle off for speed when using Excel Macro)



For greater accuracy without sacrificing speed, the intersection of MPE(z) and spenergydensity(z) can be interpolated.

$$\mathrm{intercept}(E,M) := \left|\begin{array}{l} \text{for } i \in \mathrm{zstart}, \mathrm{zstart}+\mathrm{zinc} .. \mathrm{zend} \\ \quad C_i \leftarrow \mathrm{if}\left(E_i > M_i, i, 0\right) \\ x1 \leftarrow \max(C) \\ ye1 \leftarrow E_{\max(C)} \\ ye2 \leftarrow E_{\max(C)+\mathrm{zinc}} \\ dye \leftarrow ye2 - ye1 \\ me \leftarrow \dfrac{dye}{\mathrm{zinc}} \\ ce \leftarrow ye1 - me \cdot x1 \\ yn1 \leftarrow M_{\max(C)} \\ yn2 \leftarrow M_{\max(C)+\mathrm{zinc}} \\ dyn \leftarrow yn2 - yn1 \\ mn \leftarrow \dfrac{dyn}{\mathrm{zinc}} \\ cn \leftarrow yn1 - mn \cdot x1 \\ \mathrm{intercept} \leftarrow \dfrac{cn - ce}{me - mn} \\ \mathrm{intercept} \end{array}\right.$$

Subroutine to find the intersection of two lines E (energy density) and M (MPE) by linear interpolation

$\mathrm{NOHDopt} := \mathrm{intercept}\left(\mathrm{spenergydensity}, \mathrm{Re}\left(\mathrm{MPE}_{\mathrm{optical}}\right)\right)$ $\mathrm{NOHDopt} = 23.727$

$\mathrm{NOHDskin} := \mathrm{intercept}\left(\mathrm{spenergydensity}, \mathrm{Re}\left(\mathrm{MPE}_{\mathrm{skin}}\right)\right)$ $\mathrm{NOHDskin} = 1.599$

NOHDs with greater accuracy

$\mathrm{NOHDopt} := \mathrm{NOHDopt} + .01$ Avoid singularity

Finally, evaluate the number of hits and exposure time at the NOHD for the eye/binocular

$$\mathrm{Npts} := \mathrm{floor}\left(N_p(\mathrm{NN}, \mathrm{X1}(\mathrm{NOHDopt}), \mathrm{Y1}(\mathrm{NOHDopt}), \mathrm{dh}(\mathrm{NOHDopt}), \mathrm{dv}(\mathrm{NOHDopt}), \mathrm{X2}(\mathrm{NOHDopt}), \mathrm{Y2}(\mathrm{NOHDopt}), \mathrm{h}(\mathrm{NOHDopt}), \mathrm{v}(\mathrm{NOHDopt}), \mathrm{r}(\mathrm{NOHDopt}))\right)$$

$$\mathrm{EX}(z) := \mathrm{if}\left[\mathrm{npts} > N_p(\mathrm{NN}, \mathrm{X1}(z), \mathrm{Y1}(z), \mathrm{dh}(z), \mathrm{dv}(z), \mathrm{X2}(z), \mathrm{Y2}(z), \mathrm{h}(z), \mathrm{v}(z), \mathrm{r}(z)), (\mathrm{Nhoriz}(z)) \cdot \mathrm{Thoriz}, \mathrm{scantime}\right]$$

$\mathrm{TEXP} := \dfrac{\mathrm{EX}(\mathrm{NOHDopt})}{\mathrm{sec}}$ Remove units for transfer to Excel

$\mathrm{Npts} = 166$ No of hits

$\mathrm{TEXP} = 1.15$ Total exposure time

Worksheet to calculate output wavefront radius as a function of M-squared and divergence

All dims in metres, angles in mrad

$\text{lambda} := 1.54$ $\quad \lambda := \text{lambda}\cdot 10^{-6}$ $\quad \text{w\_out} := 0.01$ $\quad w_0 := \text{w\_out}$ $\quad$ Initial parameters

$\text{Msqaured} := 1.5$ $\quad \text{Msq} := \text{Msqaured}$ $\quad \text{R\_out} := -100$ $\quad R_0 := \text{R\_out}$

$$w_b(R_0, \text{Msq}, z) := \left[-\frac{\pi}{\lambda\cdot\text{Msq}}\cdot\text{Im}\left[\frac{1}{\left(\frac{1}{R_0} - \frac{i\cdot\lambda\cdot\text{Msq}}{\pi\cdot w_0^{\,2}}\right)^{-1} + z}\right]\right]^{-0.5}$$

Expression for 1/e2 radius as a function of distance

$$\text{div}(R_0, \text{Msq}) := \left(w_b(R_0, \text{Msq}, 10000) - w_b(R_0, \text{Msq}, 9000)\right)\cdot 2$$

$\text{div}(R_0, \text{Msq}) = 0.248$ divergence for given radius and Msquared

$\text{MINdiv} := \text{div}(10^6, \text{Msq})$ minimum possible divergence

---

$R_0 := -200$

Solve block to find divergence for given R, Msquared

Given

$$\text{div} = \left[\left[-\frac{\pi}{\lambda\cdot\text{Msq}}\cdot\text{Im}\left[\frac{1}{\left(\frac{1}{R_0} - \frac{i\cdot\lambda\cdot\text{Msq}}{\pi\cdot w_0^{\,2}}\right)^{-1} + 10000}\right]\right]^{-0.5} - \left[-\frac{\pi}{\lambda\cdot\text{Msq}}\cdot\text{Im}\left[\frac{1}{\left(\frac{1}{R_0} - \frac{i\cdot\lambda\cdot\text{Msq}}{\pi\cdot w_0^{\,2}}\right)^{-1} + 9000}\right]\right]^{-0.5}\right]\cdot 2$$

$R(\text{Msq}, \text{div}) := \text{Find}(R_0)$

Range may need to be adjusted to allow for minimum possible divergence of

$i := 2..10$ $\quad \text{MINdiv} = 0.147$ mrad

$R(1.5, i\cdot 0.1)$

-147.538
-76.486
53.765
41.851
34.382
29.224
25.433
22.525
20.22

Results for R with Msquared = 1.5, divergence from 0.2 to 1 mrad

Calculation of Hazard Distances for Scanning, Repetitively Pulsed Laser Systems

Alasdair McInnes and James Richards

AUSTRALIA

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